Technical Information

Capacitive Leakage Currents

Information on the design of transformerless inverters of type **Sunny Boy, Sunny Mini Central, Sunny Tripower**

The way PV modules are designed means that they always exhibit capacitance towards their environment. This capacitance is not required for the function of the PV array, but comes about essentially from the mechanical structure of the modules and their installation, and is therefore also known as "parasitic" capacitance. In particular, this capacitance increases with the conductive surfaces present in the the PV array. Consequently, a large, powerful PV field exhibits a correspondingly large parasitic capacitance which will increase even further if the surfaces are damp (e.g. from rain, condensation).

This phenomenon does not affect the insulation of the PV modules in any way, so personal safety is of course guaranteed at all times. However, the operating behavior of the inverters may be influenced by parasitic capacitance. If transformerless (TL) inverters are used, so-called displacement currents can occur which are capable of tripping the residual current monitoring of the inverter or even that of the feed-in line. In the former case, this causes the inverter to temporarily disconnect from the utility grid, after which it will automatically revert to feed-in operation. In the latter case, feed-in will be interrupted until the residual-current device (RCD) of the feed-in line has been manually reactivated.

Feed-in interruptions of this kind can be largely prevented by careful and professional system planning. In the following, we will therefore be explaining the crucial technical aspects to be taken into account in the planning phase, as well as during installation and commissioning of a PV system. This technical information is intended for two distinct groups: firstly, for manufacturers of the PV modules, with a request to pass it on to their customers, and secondly, for PV system planners and installers.

1 How is the PV Capacitance to Ground of the PV Array Calculated?

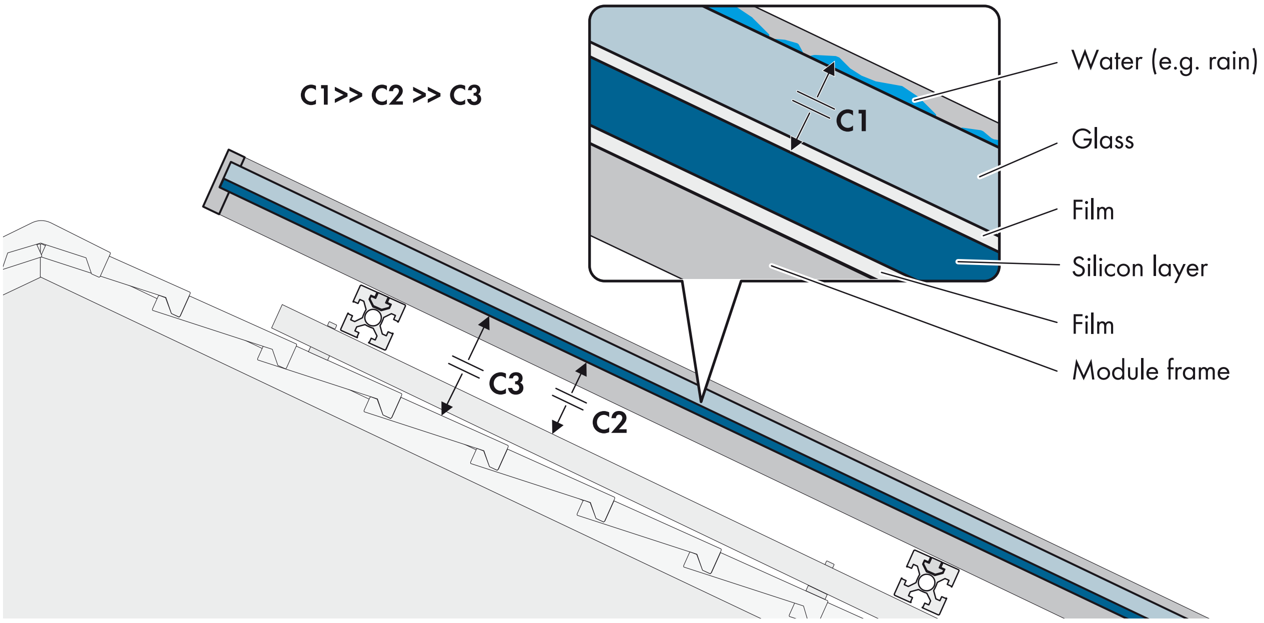

Figure 1: Illustration of a roof assembly of a PV module and schematic illustration of "parasitic capacitance"

C1	Parasitic capacitance due to film of water on the glass
C2	Parasitic capacitance due to grounded support frame
C3	Parasitic capacitance due to roof surface area

A PV module forms an electrically conductive surface which faces a grounded support frame. This type of arrangement, which stores charge when voltage is applied, is referred to as a capacitor and its capacitance as "C". Since this capacitance occurs as an undesirable side-effect, it is referred to as "parasitic capacitance" C_{PE}, which is made up of the sum of all individual capacitances:

$$C_{PE} = C1 + C2 + C3$$

The capacitance is calculated using the following formula and it depends on four factors:

$$C = \varepsilon_0 \varepsilon_r \cdot A/d$$

Meaning of the factors:

ε_0: vacuum permittivity, physical constant (8.85 • 10-12 As/Vm)

ε_r: relative permittivity, dependent on material ($\varepsilon_{rAir} = 1$; $\varepsilon_{rGlass} \approx 5 – 10$)

A: electrically effective surface area of the capacitor

d: distance between the capacitor plates

What values are to be assumed for the surface area A and distance d? This is not always easy to determine because, in addition to the data of the PV module, the type of mounting must also be taken into consideration. For this reason, there is generally no value specified in the datasheet. The following two examples will be used to demonstrate how an estimation can nevertheless be made ($\varepsilon_r = 6$ is assumed for the glass used).

For the value of the parasitic capacitance in Figure 1, the following relation is valid in rainy and wet conditions:

C1 >> C2 >> C3

This reveals that in rainy and wet conditions, the overall capacitance C_{PE} is dominated by C1, so for the purposes of further consideration, C2 and C3 can be neglected. In dry conditions, on the other hand, C1 is so small that the other parasitic capacitances must be taken into consideration. However, the overall capacitance C_{PE} remains so small that any effect on the operating behaviour of the PV system is negligible. The value of C1 during rainy and wet conditions will therefore be the subject of further consideration in this document.

Examples for Estimation of the Parasitic Capacitance C_{PE} with Different Module Types Assuming a Continuous Film of Water on the Glass Surface

Example 1: Standard module with crystalline silicon cells (monocrystalline, polycrystalline)

- Typical efficiency: 15% to 20%
- Thickness of glass: 3 mm to 4 mm
- Per m^2 module surface, the module has a capacitance of 12 nF to 17 nF
- Per kW of installed DC power, the PV system has a capacitance of 60 nF to 110 nF
- For a 5 kW PV system, this means that the C_{PE} value is 330 nF to 550 nF

Example 2: Thin-film module, e.g. CdTe

- Typical efficiency: 10% to 15%
- Thickness of glass: 3.2 mm
- Per m^2 module surface, the module has a capacitance of 16 nF
- Per kW of installed DC power, the PV system has a capacitance of 100 nF to 160 nF
- For a 5 kW PV system, this means that the C_{PE} value is 500 nF to 800 nF

2 How Does a Capacitive Leakage Current Occur?

During operation the PV modules are connected to the AC grid via the inverter. Thus, depending on the device type, a portion of the alternating voltage amplitude arrives at the PV module. As a result, the complete PV array oscillates with an alternating voltage in relation to its environment. At this point, two cases must be distinguished (see illustration):

Transformerless Inverters

In almost all **single-phase** transformerless inverters, for operational reasons, half of the grid amplitude is passed on to the PV module. In many European utility grids with 230 V/50 Hz, this arrangement oscillates, for instance, at 115 V/50 Hz. This applies to Sunny Boy and Sunny Mini Central inverters with the suffix "TL" in the product name.

In **three-phase** transformerless inverters, for systemic reasons, the oscillations are of a much smaller amplitude and, as a result, they generate smaller leakage currents. The pass-through of AC voltage to the PV module is largely suppressed. This applies to all Sunny Tripower inverters.

Inverters with Transformers

In inverters with transformers, the voltage within the PV module oscillates as a mere "ripple" of just a few volts. This gives rise to a small AC voltage in relation to the environment (electrical designation: "ground") which, however, is not uniform over the total PV array.

This fluctuating voltage constantly changes the state of charge of the parasitic capacitor described in the previous section. This is associated with a displacement current, which is proportional to the capacitance and the applied voltage amplitude. The electric circuit of this displacement current is connected to the house connection initially via the ground connection of the PV modules and that of the grounding busbar. Therefore, this current is also referred to as (capacitive) leakage current.

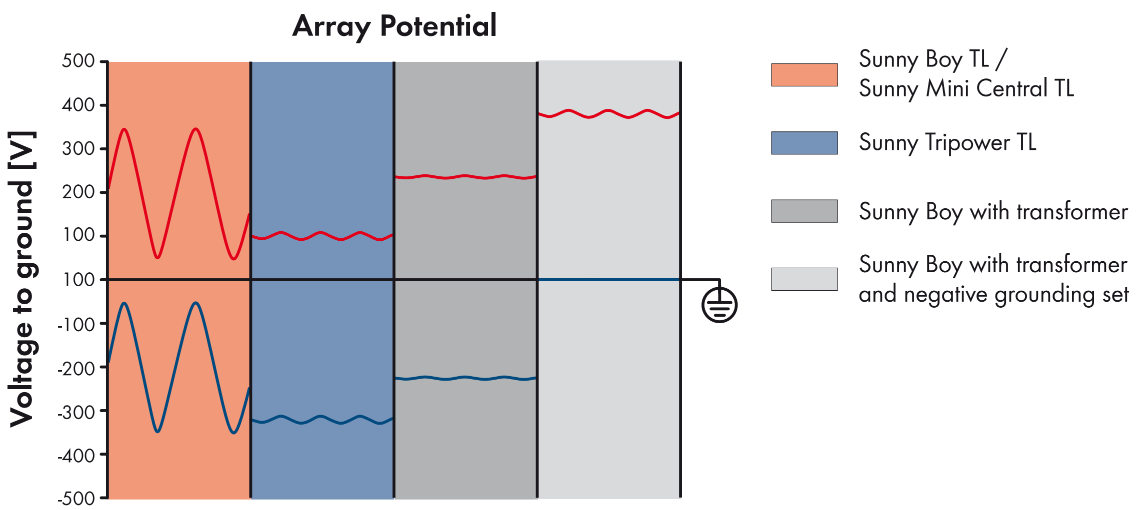

Figure 2: The potential of the lowest (blue) or highest (red) PV module of a string depends on the inverter used and whether an array pole is grounded. Example for an MPP voltage of 400 V

For experts: The physical description of the displacement current I (RMS value) is as follows:

$$I = \frac{\Delta Q}{\Delta t} = C \cdot \frac{\Delta U}{\Delta t} = C\,2 \cdot \pi \cdot f \cdot U$$

Here, f = 50 Hz is the power frequency and V is the RMS value of the alternating voltage at the PV array (115 V with 1-phase transformerless inverters). This leakage current is a reactive current with its phase rotated by 90° to the line voltage. In the first approximation, it is without loss.

3 How Does the Leakage Current Affect the Detection of the Residual Current?

The capacitive leakage current described in Section 2 is a reactive current (without loss).

However, if a fault such as a defective insulation causes a live line to come into contact with a grounded person (see Figure 3), an additional current flows to ground. This unwanted current causes losses and is referred to as residual current. The total of both currents (leakage current and residual current) is the differential current.

Differential current = leakage current + residual current

AC residual currents greater than 30 mA can be life-threatening.

In order to provide personal safety, in addition to the protection class of the PV array, transformerless inverters must be disconnected from the utility grid immediately upon occurrence of a residual current of 30 mA (DIN VDE 0126-1-1). For this purpose, during feed-in operation, the differential current (leakage current + residual current) is measured using an all-pole sensitive residual-current monitoring unit (RCMU). However, this can only measure the differential current (leakage current + residual current). It is only possible to factor out the residual current to a limited extent, and this becomes more difficult with increasing leakage current. From approximately 50 mA upwards, random fluctuations in the leakage current become so great that they can be interpreted as sudden surges of residual current of over 30 mA. In such cases, the inverter disconnects automatically from the utility grid as a preventative measure.

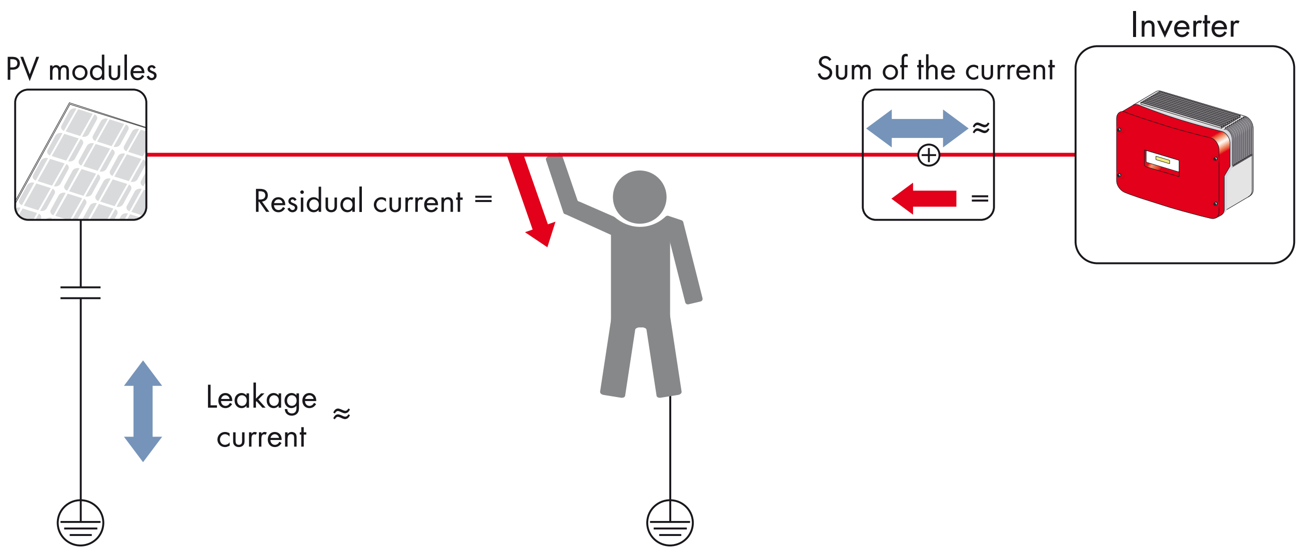

Figure 3: Formation of residual current through contact between a grounded person and a live line

4 At What Point Does it Become Problematic?

Capacitance Limit

As previously described, leakage currents of more than 50 mA should be avoided in order to ensure that the residual current monitoring of the PV array will still function normally.

Since the leakage current is directly dependent on the capacitance of the PV module to ground, for each line voltage a capacitance limit can be specified, above which operation will be susceptible to disturbances.

For all single-phase transformerless inverters, we derive in accordance with the formula above:

$I = C \cdot 2\pi \cdot f \cdot V$ (when I = 50 mA, f = 50 Hz and V = 115 V) a capacitance limit of approximately 1,400 nF. For the Sunny Tripower, the capacitance limit is 2,560 nF.

These capacitances are rarely reached in practice. A comprehensive field study has shown that for most glass-glass modules, the rule of thumb values below are peak values that are only achieved in the event of very heavy rainfall. The values are also higher if there is morning condensation, but drop to very low values during times of highest yield (sunshine). In the following figure, the reaction of the leakage current of a PV array to such events can be seen.

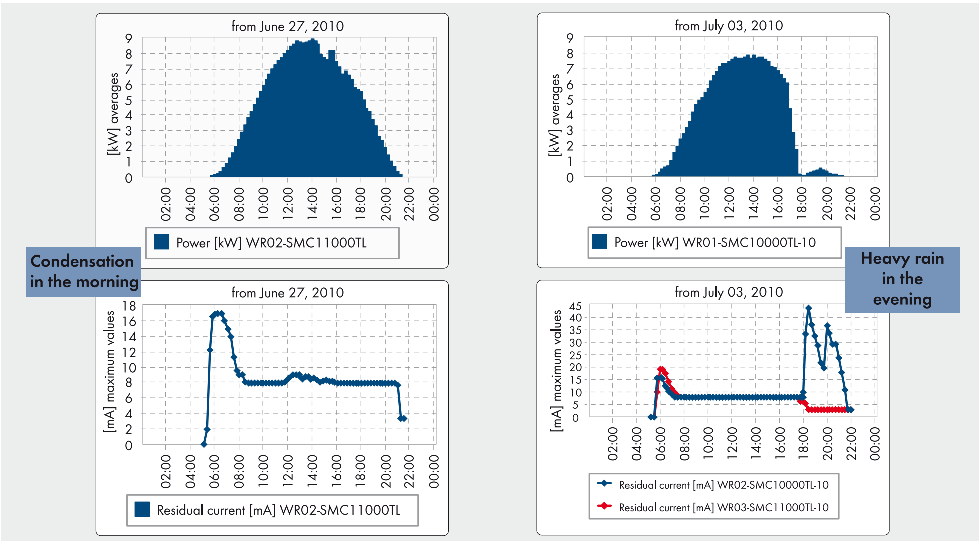

Figure 4: Pattern of leakage current as a reaction to the change in parasitic array capacitance of glass-glass modules in the event of condensation and heavy rainfall

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For experts: rule of thumb for the capacitance of a PV module

Insert the following values into the above mentioned formula for the capacitance:

$\varepsilon_0 = 8.85 \cdot 10^{-12}$ As / Vm

$\varepsilon_{rGlas} = 6$

Then, $C = \varepsilon_0 \varepsilon_r \cdot A / d \rightarrow C\,[nF] \approx 50 \cdot A\,[m^2] / d\,[mm]$.

The following approximation formula applies:

$C\,[nF] \approx 50 \cdot A\,[m^2] / d\,[mm]$

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5 Use of a Residual-Current Device with Sunny Tripower

In utility grids without disturbances, three-phase symmetrical feed-in is associated with a very low leakage current. The inverters STP 5000TL-20, STP 6000TL-20, STP 7000TL-20, STP 8000TL-20, STP 9000TL-20, STP 10000TL-20, STP 12000TL-20 can also be operated with a special control procedure that reduces the operational leakage current.

In this case, each inverter must be connected to the utility grid using a separate, external residual-current device.

If you are using an external 30 mA residual-current device, the tripping level of the residual-current monitoring in the inverter must be set via parameters to max. 30 mA (see the inverter documentation at www.SMA-Solar.com). This will ensure that the internal residual-current monitoring of the inverter will respond to an error before the external residual-current device.

6 Compensation of Capacitive Leakage Currents

The situation described in the previous sections for differential-current monitoring in the inverter can also be applied to residual-current monitoring during feed-in. Local directives may prescribe the installation of a residual-current device (RCD) for the utility grid/feed-in line of the PV array. During bad weather, e.g. heavy rain, the leakage capacitance of the PV array can increase to such an extent that the resulting capacitive leakage current trips the residual-current device even though no residual current is present. This is just what happens frequently with residual-current devices with a low residual-current tripping threshold (e.g. of 30 mA).

If the residual-current device is tripped as a result of a capacitive leakage current and is not promptly switched back on, significant yield losses may result.

In the case of single-phase feed-in, this situation can be significantly alleviated by the use of a four-pole residual-current device in place of the regular two-pole alternating current device and by connecting an external capacitor. The external capacitor generates a compensation current that reduces the capacitive leakage current by a constant amount. This prevents early tripping of the residual-current device due to capacitive leakage current, and we find the following relationship:

Differential current = leakage current + residual current - compensation current

Behavior of a Residual-Current Device

Residual-current devices always have a reference nominal residual current value at which they must trip.

The tripping threshold and tolerances depend, among other things, on the type of the residual-current device. Depending on the expected operating current, we distinguish between the following types: A, B and AC.

The tripping threshold of a residual-current device of type A typically operates in the tolerance range +0%/-50%. This means that, for example, a residual-current device with I_{NOM} = 30 mA must reliably trip from a differential current of 30 mA, but must not trip below 15 mA. In practice, it always trips somewhere between 15 mA and 30 mA.

Tripping Behavior with Compensation Current

The compensation current influences the tripping behavior of the residual-current device, as can be seen in the following example.

Example: In a PV array with a residual-current device on the AC side which trips at 30 mA, a heavy rain shower leads to a capacitive leakage current of I_c = 24 mA. In normal circumstances, this could cause the residual-current device to trip.

With a compensation current of I_{comp} = 13 mA, the effective differential current in the residual-current device can be reduced by this amount, so that the resulting leakage current then amounts to

$I_{cap\ net}$ = 24 mA - 13 mA = 11 mA. Hence, tripping of the residual-current device due to the rain-induced leakage current can be prevented.

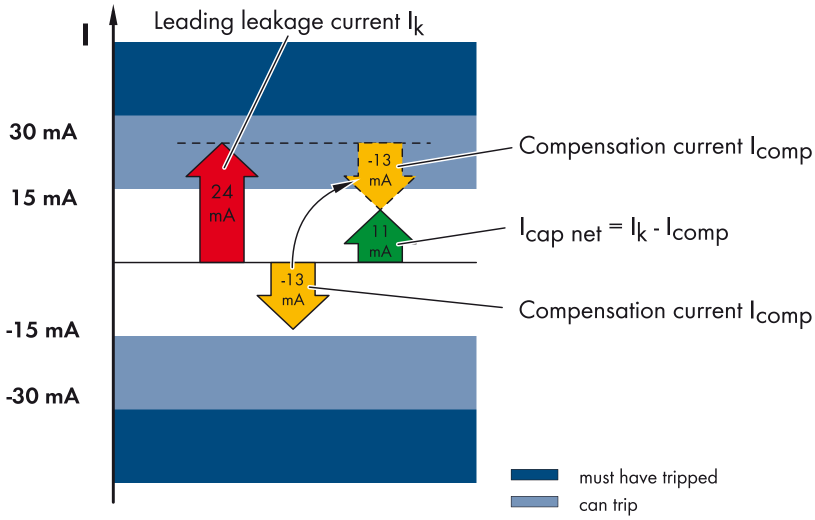

Figure 5: Diagram of tripping behavior with compensation current

Sizing of a Compensation Capacitor

When sizing a capacitor, it should be ensured that the compensation current is always smaller than the lower tripping threshold, as otherwise the compensation current itself would cause the residual-current device to trip.

The capacitance C_{comp} of the compensation capacitor can be determined as follows:

$$C_{comp} = I_{comp}/(V_{grid} \times 2\pi f)$$

where

V_{grid} = 230 V

f = 50 Hz

I_{comp} = desired compensation current

For I_{comp} < 15 mA, this means a capacitor with a maximum capacitance of C_{comp} < 208 nF is needed

Here, the next lowest standard value is used with C_{comp} = 150 nF (+/-20%) and an actual compensation current of I_{comp} = 11 mA (+/-20%)

Additional properties of the capacitor:

- Type: class X2
- Pulse peak voltage during operation ≥ 2.5 kV
- Nominal voltage: at least 230 V AC

Sizing table:

In the case of residual-current devices with greater nominal currents, the compensation current can be increased correspondingly in order to reduce the likelihood of unintended tripping as a result of capacitive leakage currents.

Residual-current device nominal current	Lower tripping threshold (-50% I_{nom})	Recommended capacitance	Compensation current
30 mA	15 mA	150 nF	11 mA
50 mA	25 mA	330 nF	24 mA

Effectiveness of the residual-current device

The effectiveness of the residual-current device when residual current actually occurs remains intact even if such measures for compensation of leakage current have been implemented.

Connecting the Compensation Current Capacitor to the Residual-Current Device

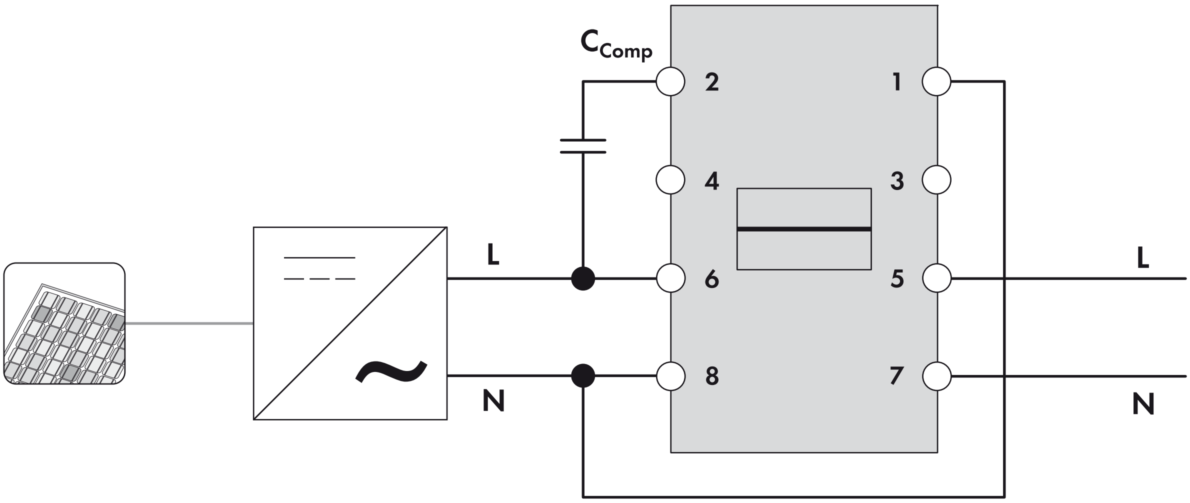

Figure 6: Schematic illustration of the connection of a compensation capacitor to the residual-current device

Conclusion

The compensation of leakage currents using the method described above can provide effective support in systems where the residual-current device may occasionally be tripped as a result of bad weather (e.g. heavy rain), and it can also reduce the tripping frequency or even eliminate it altogether.

7 Checklist

During the planning phase, every PV system should be reviewed based on the requirements specified in the above sections. In addition, we recommend the following test steps:

Test Step 1

The PV module under review exhibits a high design-related capacitance to ground C_{PE} (laminate, integrated metal rear panel), or it is necessary to reliably prevent feed-in interruptions due to rain/condensation. Determine the critical capacitance to ground as follows:

1. Calculate the total module surface A of the modules connected to one inverter.
2. Identify the smallest distance d of the PV cells to a conductive surface.

   This conductive surface may only be conductive at certain times (e.g. under conditions of rain or condensation). Therefore, in the event of rainfall the thickness of the cover glass, and in the event of condensation the thickness of the rear-panel insulation, is critical for the distance d.
3. Enter the values in the calculation formula (see Section 1 "How is the PV Capacitance to Ground of the PV Array Calculated?", page 2) to determine the capacitance.

   or
4. Use the diagram below to check whether the operating point derived from the module surface area A and the surface distance d is above the limit shown for the given inverter type.

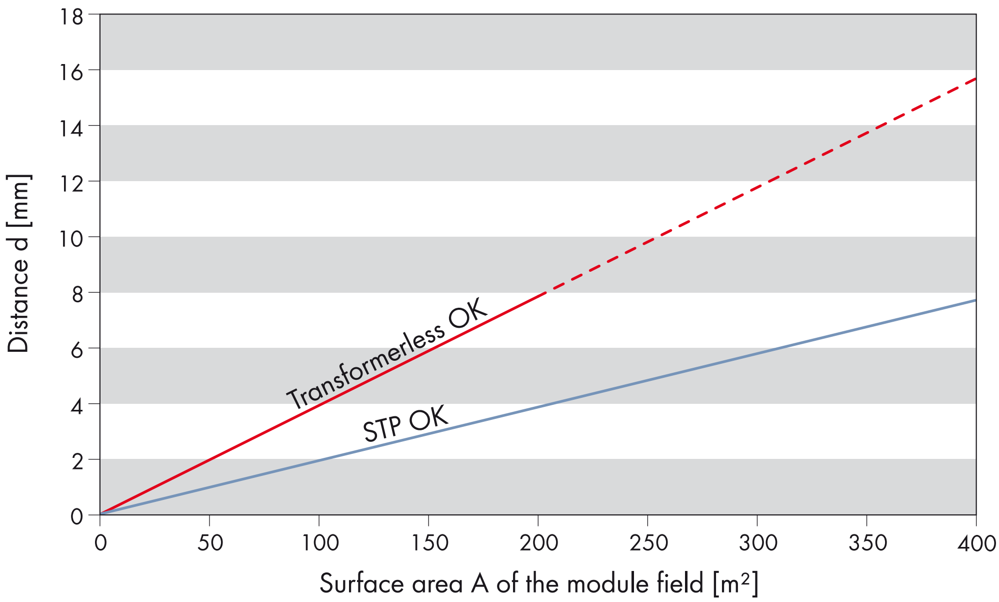

Figure 7: Minimum distance of PV cells to grounded surfaces for single-phase and three-phase transformerless inverters. The operating point of a PV system should always be above the corresponding limit line.

Test Step 2

When the capacitance to ground C_{PE} is in the critical range (Sunny Boy > 1,400 nF; Sunny Tripower > 2,560 nF, or the operating point is under the corresponding limit line in the diagram), measures for preventing feed-in interruptions should be considered:

- Compensation of the residual-current device in single-phase feed-in systems
- Use of an external residual-current device with higher operating current
- Deployment of a Sunny Tripower instead of a Sunny Boy
- Segmentation of one PV array into smaller substrings
- Use of an inverter with a transformer

Test Step 3

Consult the PV module manufacturer. Is there any known data on parasitic capacitance?

In cases of doubt, we strongly recommend involving the PV module manufacturer in the planning process. This applies particularly in cases where the operator does not have any first-hand experience of combining a PV module type with a transformerless inverter.

Contact

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